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ADDRESSING NO_X – SMOKE TRADE OFF IN A DIRECTION INJECTION DIESEL ENGINE WITH FUEL BLENDS OF DIETHYL ETHER AND DIESEL

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ABSTRACT

In this research work, an experimental investigation was carried out to study the combustion, performance and emission characteristics of a single cylinder water cooled diesel engine, when fueled with blends of diethyl ether and diesel. Three different blends with 5%, 10% and 15% of diethyl ether were tested and compared with neat diesel fuel at different load conditions. Fuel consumption, in-cylinder pressure and exhaust emissions were measured at all load conditions. When compared to neat diesel fuel, the blends of diethyl ether exhibited reduced carbon monoxide, nitrogen oxide and smoke emissions with increased hydrocarbon emissions. Lower brake specific energy consumption and increased brake thermal efficiency were observed for the blended fuels. The in-cylinder peak pressure and the heat release rate for blended fuels were lower compared to the diesel fuel. It was evident from the experimental results that 15% of diethyl ether blend has the potential of overcoming the existing NO_x-smoke trade-off in diesel engines.

KEYWORDS: Combustion; DEE; Diesel Blends; Nitrogen Oxides; No_x-Smoke & Trade-Off

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Original Article

INTRODUCTION

The rapid urbanization, increased vehicular population and the decreasing fossil fuels availability are demanding the effective utilization of the available fuels. Although compression ignited (CI) engines have higher fuel conversion efficiency, it produces a high level of nitrogen oxides and greenhouse gas emissions, and due to the non-homogeneous mixture formation inside the combustion chamber. Stringent emission norms and the need to improve the power output with reduced engine size have made the global researchers to adopt different strategies for meeting the requirement. One such technique involves the modification of fuel properties either by blending different fuels or completely replacing the diesel fuel with alternate fuels. The blending of different fuels can alter the fuel composition and properties greatly, which can further impact the combustion process. Increasing the percentage of oxygen in the fuel could increase the possibility of complete combustion and hence the fuel conversion efficiency.

Substantial reduction in smoke, carbon monoxide and UN burnt hydrocarbon emissions is also possible with the presence of excess oxygen. The oxygen composition in the combustion chamber can be increased by adding oxygenates with the diesel fuel. Oxygenates are the hydrocarbons which contain oxygen within them. Ethanol, Dibutyl Ether (DBE) and Methanol are widely used by various researchers, to increase the oxygen content in the fuel[1]. Ethanol, due to its higher octane value, is preferred in SI engines to improve the combustion. On the other hand, the certain value of ethanol is poor, due to which it is not preferred in CI engines. When ethanol is dehydrated, Diethyl Ether (DEE)which has higher cetane number (>125) is obtained and this could serve as a

better fuel for CI engines[2]. In comparison to neat diesel, DEE has the potential of supplementing the fuel with oxygen to improve combustion and emission characteristics of diesel engines [3].

DEE can be used as an engine fuel in two ways: either through intake manifold induction or blending with the main fuel as additives. When DEE is inducted in the manifold, it vaporises quickly and mixes with air well due to its higher saturation pressure. The presence of DEE in the air accelerates the combustion process inside the engine[4]. In addition, the premixing of DEE with the air can considerably reduce the emission levels. Studies by Cinar et al.[5] on a homogeneous charge compression ignition (HCCI) direct injection (DI) diesel engine concluded that significant reduction in the smoke and NO_x could be achieved with 10 % premixed fuel ratio (PFR) of DEE. It was also reported that higher percentage of PFR (> 40%) led to abnormal engine combustion and cycle to cycle variation was reduced when premixed with DEE.

The addition of 5% DEE as an additive to diesel fuel improved the engine performance and reduces the smoke, carbon monoxide and hydrocarbon emissions substantially when compared to neat diesel fuel [6]. Due to the improved combustion characteristics, the in-cylinder gas temperature increases, resulting in increased nitrogen oxide emissions when blended with diethyl ether [7].

The addition of diethyl ether in different proportions (5,10 and 15% by wt.) with diesel-water emulsion was found to improve the performance and emission characteristics[8]. DEE can also be effectively blended with biodiesel. The experiments carried out by Iran Manesh et al.[9]showed that the smoke and nitrogen oxides can be considerably reduced with the addition of DEE to Karanja oil methyl esters. A similar kind of results was also reported by Qi et al. [10], where 5% DEE was added to the soybean based biodiesel-diesel blend. The presence of DEE reduced the carbon monoxide emissions with increased hydrocarbon emissions.

In spite of higher cetane number of DEE over neat diesel, the studies conducted by Rakopoulus et al.[11,12]indicated that, the ignition delay period was getting increased when DEE was blended with diesel fuel. Moreover, lower in-cylinder pressure and temperature were reported or DEE blends than neat diesel. On the contrary, Sivalakshmi and Balu Samy [13] exhibited that, the peak pressure and temperature were getting increased with the blend of DEE and thus increased NO_x emission. Ali et al.[14]and Ibrahim [15]indicated that, addition of DEE as blend increases the cycle to cycle variation in a diesel engine. The injection of a small quantity (4%) of DEE into the engine fuelled with Karanja methyl ester and biogas, has improved the combustion and emission parameters[16].

The use of DEE as straight fuel or blends with diesel fuel can enhance the cavitations phenomenon inside the fuel injector during the injection process. Studies had shown that cavitation inside the injector assists the fuel spray in better mixing with air[17,18]. Due to its higher saturation pressure, DEE tends to cavitate more compared to diesel, thereby increasing the exit velocity of the fuel from the injector which may increase the depth of penetration off or the fuel[19,20].

The above literature study shows the effective usage of diethyl ether as blended fuel in a diesel engine. The study also indicated the contradictory information about the combustion behaviour of diethyl ether when it is blended with diesel fuel. In this work, three blends of diethyl ether (5, 10, and 15% by vol.) with diesel are tested and the combustion, performance and emission characteristics are analysed.

EXPERIMENTAL SETUP AND METHODOLOGY

The schematic representation of the experimental setup is shown in Figure. 1. A single cylinder, 4 stroke water-cooled direct injection diesel engine was used for the experimentation. The major specifications of the test engine are presented in Table 1. The engine was coupled to an eddy current dynamometer. The output power was directly obtained with the accurate measurement of reaction torque using a strain gauge type load cell.

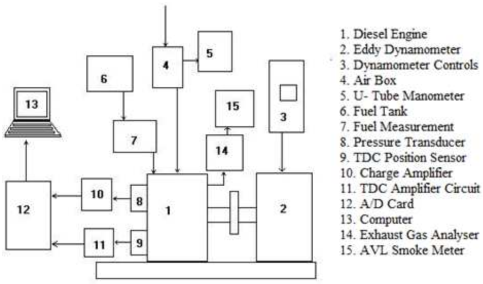

Figure 1: Schematic of the Experimental Setup

Table 1: Specifications of Test Engine

Parameter	Value
Engine type	Four stroke, water cooled, single cylinder direct injection diesel engine
Engine make and type	Kirloskar TV1
Bore, mm	87.5
Stroke, mm	110
Compression ratio	17.5: 1
Rated power, kW	5.2 kW @ 1500 rpm
Static injection timing	23° bTDC
Injection pressure, bar	205

The pressure inside the combustion chamber was measured using an AVL GH12D miniature pressure transducer connected to an AVL3066A02 piezo charge amplifier. The crank angle and the position of top dead centre (TDC) were measured using an AVL364 angle encoder, mounted rigidly on the camshaft of the engine. The outputs of the charge amplifier and the encoder were connected to an AVL 615 In dimeter A/D card, which converts analog input to digital output. A thermocouple in the exhaust pipe measuring the exhaust gas temperature was considered as an indication of temperature obtained in the combustion chamber as a result of combustion of fuel.

Testing Procedure

The properties comparison of DEE and diesel fuel [21]is shown in Table 2. The engine was fuelled with blends of DEE and diesel. DEE was directly mixed under standard atmospheric condition and blends of 5%, 10%, and 15% were prepared. The prepared blends were then fed to the engine through a direct injection system. Engine testing was carried out at various loads starting from no load to peak load. At each load, the engine was operated for 5 minutes, to stabilize the engine under new conditions. The tests were conducted at the rated engine speed. The engine was first fuelled with diesel oil, and under the steady state conditions, the combustion parameters were recorded at various loads. The engine was then fuelled with DEE blends and the tests were performed. Various parameters were measured and the results were tabulated.

Table 2: Properties of Dee and Diesel

Fuel Property	DEE	Diesel
Carbon weight %	64.7	83
Hydrogen weight %	13.5	17
Oxygen weight %	21.6	0
Density @ 25°C (kg/m^3)	713.4	822
Viscosity @ 25°C (kg-m/s)	0.0002448	0.00224
Auto ignition point (°C)	160	210-220
Vapor pressure @ 25°C (Pa)	58660	1280
Lower heating value (MJ/kg)	33.9	43.4
Cetane Number	>125	45-60
Boiling Point (°C)	35	180-360
Latent Heat of Evaporation (kJ/kg)	355	250
Bulk Modulus of Elasticity, bar	13100	15450

Uncertainty Analysis

The maximum possible errors associated with measurements of pressure, temperatures and in calculations of combustion parameters were computed using the method proposed by Moffat[22]. Errors were estimated from the minimum values of output and the accuracy of the instrument. This method is based on the careful specification of the uncertainties in the various experimental measurements.

If an estimated quantity, Q depends on independent variables like (x_1, x_2, x_3 …………x_n) then the error in the value of “Q” is given by

$$\frac{\partial Q}{Q} = \left\{ \left(\frac{\partial x_1}{x_1}\right)^2 + \left(\frac{\partial x_2}{x_2}\right)^2 + \ldots\ldots\ldots.. + \left(\frac{\partial x_n}{x_n}\right)^2 \right\}^{\frac{1}{2}}$$

where, $\left(\frac{\partial x_1}{x_1}\right), \left(\frac{\partial x_2}{x_2}\right)$ etc are the errors in the independent variables.

∂x_1 = Accuracy of the measuring instrument

x_1 =Minimum Value of the output measured

The errors in the measured quantities of major parameters were calculated and given in Table 3.

Table 3: Errors in Measured Parameters

Measured Parameter	Measuring Device	Error (%)
Exhaust gas temperature	K Type Thermocouple	0.5
Cylinder pressure	Pressure transducer	1.35
Crank angle	Angle encoder	2

RESULTS AND DISCUSSIONS

Combustion Characteristics

The combustion characteristics of any fuel are normally studied by analysing the in-cylinder pressure, the amount of energy released over the period of combustion and the rate at which the fuel mass burns.

In-Cylinder Pressure

The engine was made to run at the rated speed of 1500 rpm while the start of injection was maintained at 23° bTDC for diesel and diethyl ether blends. The in-cylinder pressure at rated load for the different fuels under investigation is shown in Figure. 2. It was evident from Figure. 2 that the peak cylinder pressures for all the test fuels were mutually comparable and show the expected trend.

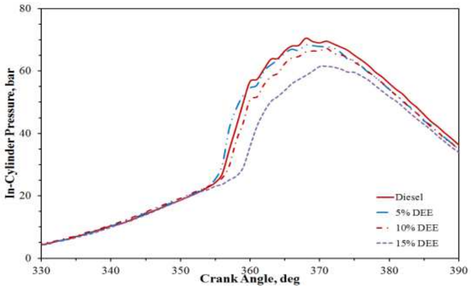

Figure 2: In-Cylinder Pressure Variation at Full Load Condition

The peak cylinder pressure for diesel fuel was around 70 bar and it was higher compared to other blended fuels. The addition of a higher percentage of DEE reduced the in-cylinder pressure due to the increased ignition delay period. Though the cetane number of DEE was higher than diesel fuel, due to its lower bulk modulus of elasticity and higher latent heat the start of ignition is delayed compared to diesel fuel [11]. Lower bulk modulus increases the time required for the fuel to reach the desired delivery pressure inside the fuel pump and hence decreases the dynamic injection timing. The higher latent heat of DEE fuel also slightly reduces the surrounding temperature compared to the diesel fuel. Hence it can be said that as the percentage of DEE increases in the diesel fuel, the actual delivery of fuel from the nozzle is delayed and hence the ignition delay period increases.

The peak pressure obtained for the blended fuels were reduced substantially. A Similar kind of results was reported by Ismet Sezer [23]. For 5% blend, the peak pressure was found to be around 68 bar whereas for 10% and 15% the peak pressures were around 63 and 58bar respectively.

The variation of peak pressures for different load conditions for all the tested fuels is shown in Figure. 3. The variation of peak pressure was higher at full load conditions than at part loads for all the blended fuels.

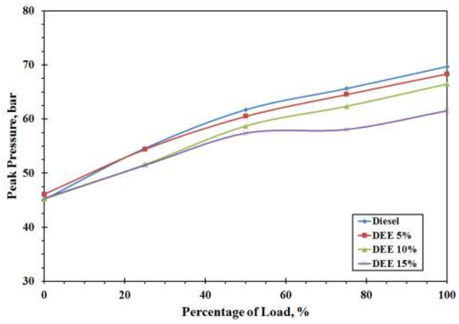

Figure3: In-Cylinder Peak Pressure Variation for all the Test Fuels

Heat Release Rate

The variation of apparent heat release rate for all the tested fuels at the full load condition is depicted in Figure. 4. As the percentage of DEE was increased, the net heat release got decreased. With 5% addition of DEE, there was no much

variation in the heat release rate. With 10% and 15% DEE-diesel blends, the start of energy release was delayed and the amount of energy released during the premixed combustion phase was reduced compared to diesel fuel [19]. The reduced calorific value of the blends and decreased injection timing reduces the amount of energy released during the premixed phase. The energy released during the diffusion combustion phase was marginally higher at 15% DEE-diesel blend indicating better mixing of fuel and air.

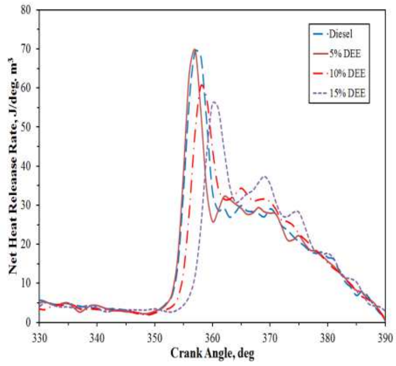

Figure 4: Net Heat Release Rate at Full Load Condition

Mass Fraction Burnt

The cumulative mass fraction burnt for all the test fuels under full load condition is presented in Figure. 5. The addition of DEE delays the start of combustion shifting the combustion phase towards the top dead centre. The end of combustion for the entire three test fuels was almost the same indicating that addition of DEE slightly reduces the overall combustion duration.

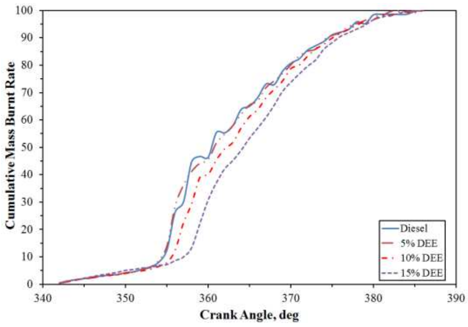

Figure 5: Cumulative Mass Fraction Burnt At Full Load Condition

Performance Characteristics

The fuels used in the test were blends of DEE and diesel with different densities and calorific values, it would be appropriate to use brake specific energy consumption rather than the brake specific fuel consumption to compare the fuels. The variation of brake specific energy consumption and fuel conversion efficiency at different load conditions for all the test fuels is shown in Figure. 6 and Figure. 7 respectively.

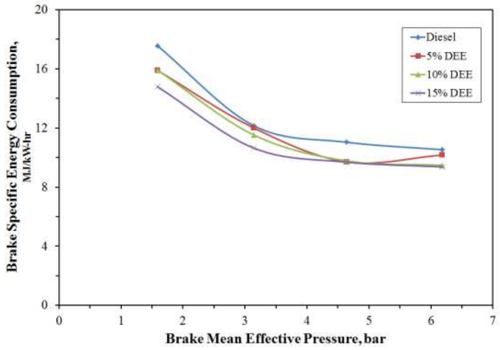

Figure 6: Break Specific Energy Consumption of the Test Fuels

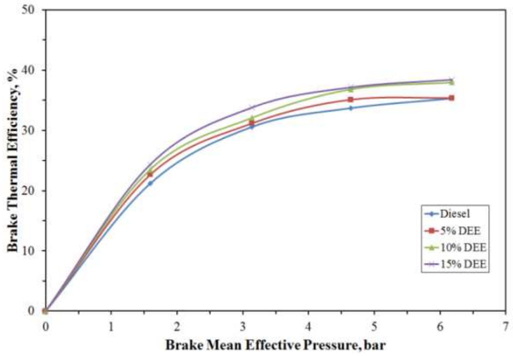

Figure 7: Brake Thermal Efficiency of the Test Fuels

The diesel and blended fuels showed almost identical fuel consumption and fuel conversion trends. The addition of DEE to diesel fuel reduces the energy consumption rate at all load conditions and improves the fuel conversion efficiency. The presence of additional oxygen in DEE helps to combust the locally rich mixture more efficiently. The higher volatility nature of the DEE helps better mixing of the fuel and air and thereby improving the combustion effectively. At full load operation with 15% DEE addition, the fuel conversion efficiency was increased by 3%. Although the calorific value of the blends is lesser than neat diesel fuel, due to the reduced in-cylinder temperature, the heat loss from the combustion chamber to the surroundings reduces and thus better mechanical conversion. It was also evident from the heat release curves; the energy released during the diffusion combustion phase was marginally higher for blended fuels, thereby improving the conversion efficiency.

EMISSION CHARACTERISTICS

Carbon Monoxide Emissions

The brake specific carbon monoxide emissions for all the test fuels are shown in Figure. 8. CO emission in diesel engines is generally formed as a result of incomplete combustion due to insufficient oxygen in the air-fuel mixture. In general, CO emission is lesser at low load conditions and increases at higher loads due to increased richness of the mixture. The trend established by the diesel and blended fuels were comparable. CO emissions for DEE blends were lesser compared to diesel fuel at all load conditions due to the presence of higher oxygen content in the fuel. Substantial reduction in CO emission was observed with an increase in the percentage of DEE in the blended fuels. About 60% reduction in CO emission was observed with 15 % DEE- diesel blend, which indicated the participation of oxygen present in the fuel for the oxidation of combustion products.

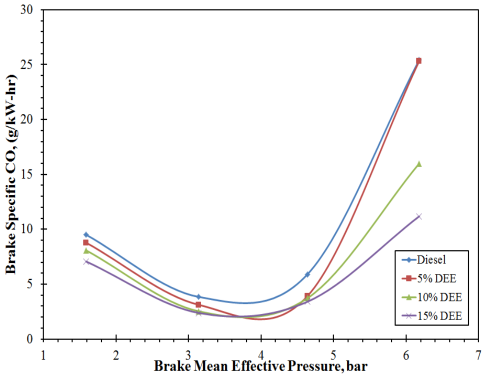

Figure 8: Variation of Brake Specific CO Emissions at different Load Conditions

Unburnt Hydrocarbon Emissions

The variation of brake specific unburnt hydrocarbon emission for all the test fuels is shown in Figure. 9. Unburnt hydrocarbon emissions are the resultant of incomplete combustion due to fuel rich mixtures formed inside the cylinder during the fuel injection process. When compared to neat diesel fuel operation, higher HC emissions were observed for the blended fuels at low load conditions. Eventhough the presence of oxygen may help in achieving better combustion, the reduction of in-cylinder temperature due to the higher latent heat of vaporization for the blended fuels and an increase in the ignition delay increases the unburnt hydrocarbon emissions substantially. As the load increases, the in-cylinder temperature increases and better mixing of fuel resulted in slightly reduced HC emissions.

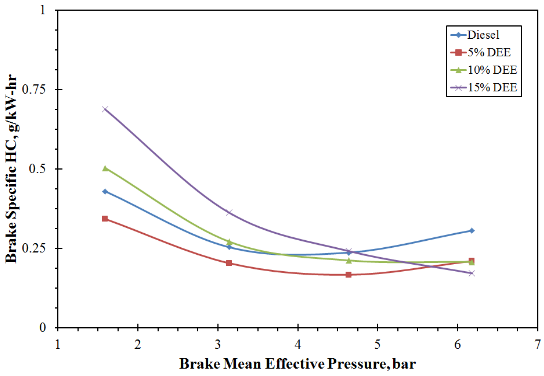

Figure 9: Variation of Brake Specific HC Emissions at Different Load Conditions

Nitrogen Oxide Emissions

The variation of brake specific nitrogen oxide emissions are shown in Figure. 10. The nitrogen oxide emissions in an engine majorly depend upon the in-cylinder combustion temperature, the oxygen concentration, the oxidation of intermediate nitrogen containing combustion products and the presence of nitrogen in the fuel. The addition of 5% DEE shows similar kind of NO_x emission, as that of diesel fuel at higher load conditions. While, the addition of DEE was increased to 15%, the NO_x emissions were found to be lower for the blended fuel compared to diesel at all load conditions.

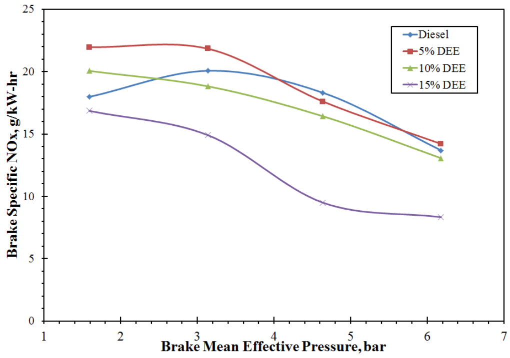

Figure 10: Variation of Brake Specific No_x Emissions at Different Load Conditions

The net heat released by the blended fuels during the premixed phase was comparatively lower than the diesel fuel resulting in reduced in-cylinder temperature. Reduced in-cylinder temperatures reduce the formation of NO_x during the combustion, even though the oxygen concentration for the blended fuels was higher. At the full load condition, NO_x emission was reduced by about 42% with the addition of 15 % DEE. The observed results are in agreement with the results reported by Rakopoulus et al.[12]and Patil et al.[24].

Smoke Emissions

The variation of smoke emissions for the test fuels at all load conditions is shown in Figure. 11. In general, the smoke opacity increases with load indicating more formation of soot particles inside the cylinder. As the load increases, the richness of the fuel-air mixture increases resulting in more soot particles. Formation of soot also depends on the rate at which the energy released during the mixing controlled phase. Higher energy release in mixing controlled phase indicate better mixing of fuel and air during combustion resulting in reduced soot particles and hence reduced smoke opacity. The addition of DEE increases the energy released during the mixing controlled phase, as observed from the heat release rate, indicating better diffusion combustion phase and hence fewer soot particles. The presence of additional oxygen in the blended fuels may favour the soot oxidation and thereby reduces the overall soot emitted by the engine. At the full load condition, the smoke opacity was reduced by about 6% for the blended fuels.

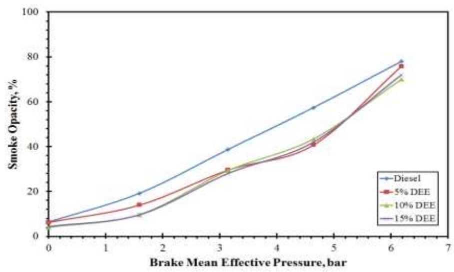

Figure 11: Variation of Smoke Opacity at Different Load Conditions

CONCLUSIONS

The potential of using diethyl ether as an alternative for diesel fuel was examined experimentally. The combustion, performance and emission characteristics of the diethyl ether blends (5%, 10% and 15%) were investigated and compared with diesel fuel and the following conclusions were drawn.

- The addition of diethyl ether reduces the dynamic injection timing and hence increases the ignition delay period compared to diesel fuel.

- The peak cylinder pressure obtained and the net energy released for the diethyl ether blends were lesser than the neat diesel operation. The net heat released during the premixed combustion phase was reduced and it was getting increased during the diffusion combustion phase for the blended fuels.
- The brake specific energy consumption rate for the blended fuels was lower compared to diesel fuels and the conversion efficiency of blended fuels was higher compared to diesel fuels at all load conditions.
- The presence of oxygen in the blended fuels promotes better combustion and hence reduces the carbon monoxide emissions substantially at all load conditions.
- The higher latent heat of vaporization of diethyl ether reduces the in-cylinder temperature slightly resulting in increased unburnt hydrocarbon emissions for the blended fuels.
- The reduced in-cylinder temperatures and the reduced energy release during the premixed combustion phase for the diethyl ether blends reduces the formation of nitrogen oxide emissions at all load conditions compared to diesel fuel.
- Increased energy release during the diffusion combustion phase reduces the soot particles formed during the combustion, indicated by the reduced smoke opacity value, for the blended fuels compared to diesel fuel.
- 15% of diethyl ether blend had the potential of overcoming the NO_x-smoke trade-off with the simultaneous reduction of NO_x and smoke emissions.

Conflict of Interest

The authors declare that there is no conflict of interest.

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